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# Research Collaboration Patterns in Sustainable Mining—A Co-Authorship Analysis of Publications

**Magdalena Bemke-Świtilnik [1,*], Aneta Drabek [2], Anna Małgorzata Kamińska [3] and Adam Smoliński [1]**

1 Central Mining Institute, Plac Gwarków 1, 40-166 Katowice, Poland; smolin@gig.katowice.pl
2 Library of the University of Silesia, Bankowa 11a, 40 007 Katowice, Poland; Aneta.Drabek@ciniba.edu.pl
3 Institute of Culture Studies, The University of Silesia, pl. Sejmu Śląskiego 1, 40-001 Katowice, Poland; anna.kaminska@us.edu.pl
* Correspondence: mbemke@gig.eu; Tel.: +48-32-259-2266

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**Abstract:** This article quantitatively examines the patterns of collaborative research in the field of sustainable development of the mining sector. The study is based on bibliographic data of 4420 Scopus index research articles published in the period 1983–2018. Both trend and network analyses were employed in this investigation. The results show a rise in the number of joint articles and in the average number of the authors per joint article. Moreover, no increase in the relative numbers of interinstitutional, international, and cross-sector articles was observed. The collaborative efforts, in terms of the co-authorships, were taken mostly among authors affiliated with the one sector—namely, science and research institutions. This indicates that funding agencies should foster more intensively the cross-sector research collaborations for sustainable mining. However, the most collaborative countries formed cross-continental clusters, thus indicating the global character of research collaboration for sustainable mining. This, in turn, can support solving mining issues with long-term implications, especially the impact of the mining industry on the environment.

**Keywords:** sustainable mining; research collaboration; co-authorship; bibliometric analysis; network analysis

## 1. Introduction

The concept of sustainable mining was born in the late 1980s, when all industries were entering the era of sustainable development. The sustainable approach in the mining sector is necessary, since the footprints of mining activity can be visible for a long time. Within the last three decades, sustainable mining has become a common worldwide issue with a growing number of research articles [1]. The Brundtland report [2] defined sustainable development as the ability to meet the basic needs of all people without compromising the needs of future generations. Based on this assumption, Allan [3] (p. 4) presented one of the first characteristics of sustainable mining, namely, ' ... the rate of use of minerals should not exceed our capacity to find new sources, acceptable substitutes or recycle' and that ' ... sustainable mining implies that industry uses the land with care and does not endanger the planet's life support systems of air, water, soils and biota.' However, sustainable mining is a much broader term as it also comprises economic, social and governmental aspects [4,5]. Sustainability in the mining sector requires a priori collaboration among the researchers, industries, institutions, and other entities like non-profit organizations or governmental agencies. A collaborative approach is crucial to face the current and future challenges of the mining sector and to find long-term solutions [6]. In the form of cross-sector partnerships, collaboration also originates from the need to assume responsibility for the impact resulting from mining activity [7–9]. Links established by researchers and industrial partners have a positive social or economic effect such as solving the problems of hazardous extractive waste or saving costs by means of new extraction technologies, respectively. The cooperation between mining companies and the researchers may be a consequence of the need to provide highly qualified staff [10], or it can bring about scientific discoveries (e.g., paleontological, mineral, archaeological, geological, botanical, etc.).

Research collaboration could be considered a multidimensional phenomenon, with numerous motivations for starting it, different types of collaboration, various contributions of team members, different ways of acknowledging it, and finally, many reasons to terminate it. Research collaboration can be defined as the joint work of the research group members or joint work of the research groups [11]. Beaver [12] claims that collaboration leads to higher research quality and publication output since the researchers working in a team can achieve more than individually. Beaver [13] also presented a list of 18 motivations of research collaboration, i.e., sharing the skills and knowledge, an opportunity to use unique equipment, materials and resources, the increase in financial support and time-saving. The latter seems to be crucial when it comes to sustainability, which 'emerges from cross-disciplinary collaboration in the science realm' [14] (p. 52). Collaboration between industrial partners and researchers can be difficult because of different approaches on various levels which can be identified at the very foundations, namely, different motivations to publish, the choice of different publication channels, the interpretation of research results, etc. [15]. However, in the case of mining science, collaboration between the researchers and industry is inevitable considering some research problems with applied character; conducting research requires data from industrial partners while solving problems by industry often requires the engagement of scientists. Nowadays, international collaboration is a focus of funding agencies. The different European Union funding programs (Horizon 2020, EIT Raw Materials, INTERREG, etc.) pay special emphasis on the collaboration of partners representing different sectors and countries. Research in the field of mining science has an international dimension since the mining industry itself is global; i.e., the development of some methods to obtain its universality requires testing under different geological and mining conditions. In the context of funding research in the field of sustainable mining (existing and future initiatives) it is important to investigate the potential in terms of the number of institutions, countries and sectors engaged in research in this field and see if this potential is used to collaborate. Since sustainability implies a priori collaboration among various groups, namely, researchers, industrial partners, and government among others, it can be assumed that collaboration in sustainable mining between different entities will be reflected in the co-authorship of the research publications. Several studies deal with this topic, yet with some limitations in the context of this study. Aznar-Sánchez, García-Gómez, Velasco-Muñoz and Carretero-Gómez [16] focused on international collaboration, but their studies are limited only to one aspect of mining activity. While English and Wang [17] examined cooperative efforts in mining research, their study is based on articles published in one journal. The study by Frame, Baum and Card [18] on co-authorship patterns explores one particular topic, namely, coal gasification, and refers to the past state (the 1970s). None of the studies mentioned above have examined comprehensively research collaboration in the field of sustainable mining.

In the paper, a bibliometric analysis of co-authorship of research articles in sustainable mining is presented. The following specific research questions are addressed:

- What are the trends in the relative numbers of joint articles and the types of joint articles (interinstitutional, international and cross-sector) over the studied period?
- What are the team sizes in terms of the number of authors, institutions, countries and sectors engaged in publication activities?
- What is the nature of networks of collaborators on different aggregation levels (countries, institution types, institutions)? Do the phenomena of cooperation in this study form sparse networks or rather dense ones? Is this density distributed equally? What are the most frequently cooperating hubs of entities?

## 2. Materials and Methods

### 2.1. Investigation of Research Collaboration Based on the Co-Authorship—Theoretical Background

One of the most straightforward ways to investigate the research collaboration is the co-authorship of publications, a bibliometric approach based on publication and citation statistics. Pioneering work in this approach was published almost six decades ago by de Solla Price [19] who drew attention to increasing research teamwork and co-authorship of publications. A joint publication is a reward for a creative collaboration of research team members [11]. Co-authorship can be formed on an informal level, such as stable relations which have evolved in time and are based on frequent contact, trust, and support extending beyond the direct aim of the collaboration [20]. Co-authors of a research publication should meet all of these four criteria: (1) Substantial contributions to the conception or design of the work; or the acquisition, analysis, and interpretation of data for the work; (2) drafting the work or revising it critically for important intellectual content; (3) final approval of the version to be published; and (4) the agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved [21]. Therefore, the joint publication can be considered a result of an interactive process between co-authors. From the individual's point of view, co-authorship has an advantage that the division of labor is efficient, and allows for a greater number of publications. The extra benefits come from co-authorship, since besides the increase of quality and productivity of research, it positively affects the visibility and impact of research [22]. Although co-authorship undoubtedly has a lot of pros, it has its cons as well. The co-authors may be in conflict reflected in different views on given parts of the text, such as the interpretation of the results [15]. Accordingly, a compromise made in such cases could be considered a disadvantage [23]. It has to be emphasized that co-authorship is an imperfect measure of collaboration since not all forms of collaboration result in co-authored articles, and not all co-authored articles are a result of collaboration [24–26]. The unjustified behavior like a ghost- and guest/honorary-authorship can also bias this indicator. While investigating co-authorship patterns, one has to take into account the differences between disciplines; in some research areas, single-authored publications dominate (i.e., pure mathematics); in others, multi-authored publications are typical (i.e., high energy physics).

### 2.2. Data Source and Search Query

The majority of bibliometric analyses use: Scopus, Web of Science (WoS) or Google Scholar (GS); or in the case of comparative studies two or more of them. Scopus and WoS are two competing databases of controlled quality, while GS is based on automatic web crawling to find research resources—thus, it is considered as a database of a different type. WoS has a long history since one of its first citation indexes was created at the turn of the 1950s and 1960s of the 20th century. Scopus is much younger (introduced in 2004), and outperforms WoS in terms of the volume of indexed sources [27]. The Scopus database was selected as a data source to perform the bibliometric analysis in this research. However, selection of this data source was based on preliminary tests of a simple search query executed both in Scopus and Web of Science Core Collection (WoS CC). The test query included the terms 'sustainab*' AND 'mining' in article titles, abstracts, and keywords. Date range comprised all available years in both databases; the closing year was 2018. The number of articles retrieved in Scopus was 27.09% higher than in WoS CC. The article titles, abstracts, and keywords retrieved from the test query have been checked in terms of their relevance to sustainable mining, which resulted in the identification of irrelevant topics, namely, 'data mining,' 'text mining' or 'urban mining' which should be excluded. On the other hand, the need for expanding the query with terms like 'mine' or 'mines' was identified at that stage, since the first query loses sight of case studies. The final search query in Scopus was: *(TITLE-ABS-KEY (sustainab*) AND TITLE-ABS-KEY (mine OR mines OR mining)) AND NOT (TITLE-ABS-KEY ("data mining" OR "text mining" OR "urban mining")) AND (EXCLUDE (PUBYEAR, 2020) OR EXCLUDE (PUBYEAR, 2019)) AND (LIMIT-TO (DOCTYPE, "ar"))*. Data were retrieved on the 29th of April 2019.

### 2.3. Data Acquisition, Cleaning and Preparation

The total number of articles in sustainable mining retrieved in Scopus was 4220. The publication set included joint articles (3070), single-authored articles (1090) and articles with no author (60). We analyzed all joint articles in terms of authors' affiliations. Among them, 60 articles did not include the affiliation of all authors, and 24 did not include complete lists of affiliations (i.e., in the three-authored paper, two authors indicated their affiliation while the third author did not); therefore, these articles were excluded from the analysis. Almost every fifth paper in sustainable mining included an author or authors who reported multiple affiliations. The indication of two or more affiliations can be related to the multiple assignment or mobility of the researcher [28]. Three approaches were identified in the literature for dealing with authors with two or more affiliations. In the first approach, all affiliations are taken into account [29]; yet, this approach does not reflect interindividual collaboration. In the second approach, the credit goes to the country where the research was carried out [30]; this approach has limited application since not all articles concerning sustainable mining are based solely on one study area. Finally, in the third approach, only the first address is considered [31]. We applied the latter in this study as it does not exaggerate countries and institution contributions. At the stage of data cleaning, we unified errors and institution names variants through web searching. However, in the case of 37 articles, some institutions could not be identified; therefore, these articles were excluded from the analysis. Consequently, the analysis was performed on 2949 articles published from 1983 to 2018 (Figure 1).

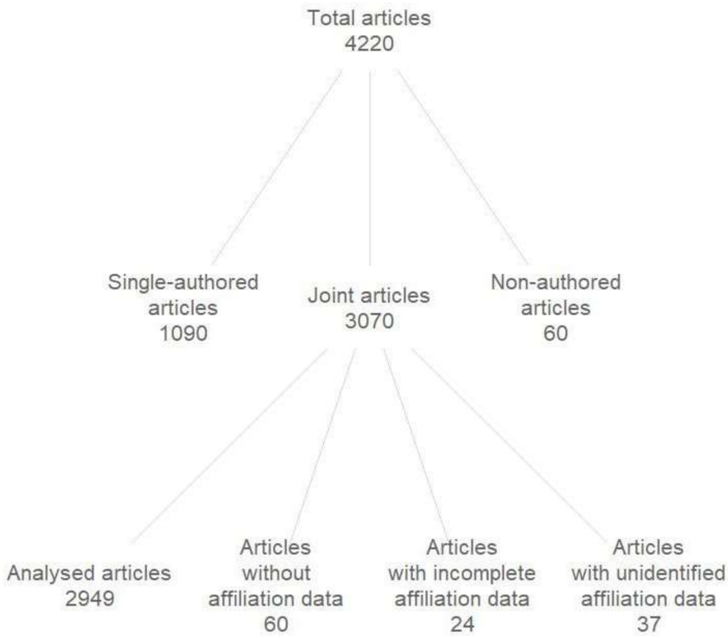


**Figure 1.** Bibliometric data selection process.

Different departments of the same institution were not considered separate units. Institutions have been attributed to their types, namely, science and research (universities, research institutes, academy of sciences, etc.), government (governmental agencies, offices, institutions and organizations), private sector (companies, corporations, mines), NPOs (non-profit organizations) and others (all institutions which could not be assigned to any of the previous groups). These types of institutions were considered in terms of cross-sector articles analysis. Detailed data were presented in Supplementary Materials available online through Zenodo at https://doi.org/10.5281/zenodo.3783598.

### 2.4. Trend and Network Analysis

In order to address the research questions formulated in the introduction, we performed a network analysis and a trend analysis enriched with descriptive statistics. Using the least squares method, we calculated linear trends using the Excel function LINEST [32]. We conducted using hypotheses test to determine whether there is a significant linear relationship between the variables. We formulated four null hypotheses which state that there is no significant trend and alternative hypotheses which state that there is a significant trend, but without specifying whether the trend would be positive (increasing) or negative (decreasing). The hypotheses were formulated to study the trends in the share of (1) joint articles in the total number of articles in sustainable mining; (2) interinstitutional articles in the total number of joint articles; (3) international articles in the total number of joint articles; and (4) cross-sector articles in the total number of joint articles. Descriptive statistics were employed to analyze the team size at different levels of data aggregation (interindividual, interinstitutional, international and cross-sector co-authorships). Regarding the network analysis, the Gephi platform was used [33]. It is a general and multipurpose tool dedicated mainly to SNA (Social Network Analysis) of many types. It is worth noting that in the field of bibliometric studies, most often other tools are chosen, e.g., VOSviewer developed by Nees Jan van Eck and Ludo Waltman [34]. This is probably due to its popularity and the ease of obtaining research data owing to the automation of data import from sources such as WoS or Crossref. However, Gephi is open-source software built as an extendable platform that brings together a large community of developers—thanks to which, it has much wider possibilities of conducting research and visualizing the results. In this study, we employed some basic functionalities of the Gephi platform, such as node degree metrics, two layout algorithms, and a community detection function implemented according to the algorithm published in [35]. More information about the application of the SNA approach to bibliometric research can be found in [36].

## 3. Results

### 3.1. Trend Analysis

The joint articles formally reflect the interindividual research collaboration. Over a period of 36 years, 72.75% of all articles in sustainable mining were joint articles ($N = 3070$). In the studied period, the average percentage of joint articles in the total number of articles accounted for 48%; the median number was 58%. The first articles in sustainable mining were published in 1983, including one joint article. However, the regular publishing efforts in terms of joint articles (meaning year by year, without any annual or longer breaks) have been taken since 1990. The smallest team size was two co-authors (the highest percentage of the two-authored articles in the total number of joint articles, namely, 30%), while the largest team consisted of 61 co-authors (only one article). The articles written by teams comprising from two to five authors constituted 83.94%. In the whole time period studied, the average team size was 3.88 co-authors. The number of joint articles correlates significantly with the total number of articles in sustainable mining (> 0.99). The annual share of joint articles in the total number of articles shows an increasing trend, and the coefficient of determination ($R^2$) implies a satisfactory fit (Figure 2). The increasing trend is statistically significant ($t = 11.1517$, $p = 2.0322$ for the 34 degrees of freedom, where $p$ is a statistic from LINEST). Figure 2 shows that the increasing trend can be observed especially from 2006. Moreover, in recent years, sustainable mining attracted more attention in terms of joint articles since about half of the total number of joint articles was published from 2014 to 2018.

In the total number of 2949 joint articles, every second article was published as a result of interinstitutional collaboration, defined in terms of articles co-signed by authors from two or more distinct institutions (53.37% in the total number of joint articles). The average percentage of interinstitutional articles in the total number of joint articles was 41% over the studied period, while the median number was 51%. The total number of 2594 institutions were engaged in joint articles. Among interinstitutional articles, collaborative efforts were taken mostly between authors from two different institutions (65.03%), and fewer between three different institutions (23.2%). Articles co-signed by authors from more than five different institutions were the minority (2.8%). The highest number of institutions involved in the co-authorship was 17, and it was related to only one article. In the studied period, the average number of institutions in the team of co-authors was 1.85. The first interinstitutional articles occurred in 1990, while regular publishing efforts concerning such articles, without any annual breaks, began three years later. The trend in the share of interinstitutional articles in the total number of joint articles shows an increase (Figure 3). The increase is statistically significant ($t$ = 3.8683, $p$ = 2.0322 for the 34 degrees of freedom, where $p$ is a statistic from LINEST); however, the low value of the coefficient of determination ($R^2$) implies an unsatisfactory fit. A closer look at the distribution displayed in Figure 3 shows that the increasing trend is rather an incidental effect. The fluctuations in the share of interinstitutional articles in the total number of joint articles were mainly between 1990 and 2004, while since 2005 the share of the interinstitutional articles in the total number of joint articles has not changed beyond minor fluctuations. The outliers visible in Figure 3, are cases of the 1990 and 1993 when all joint articles were interinstitutional.

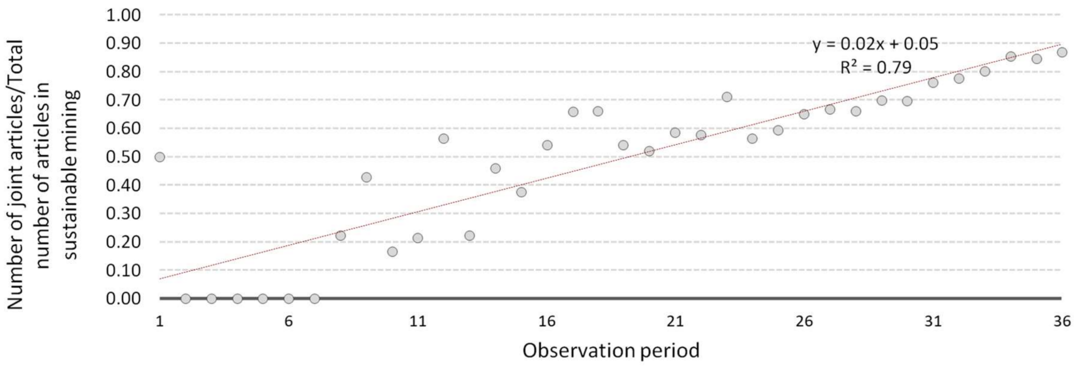


**Figure 2.** The share of the joint articles in the total number of articles in sustainable mining ($N$ = 3070). Observation period 1983–2018.

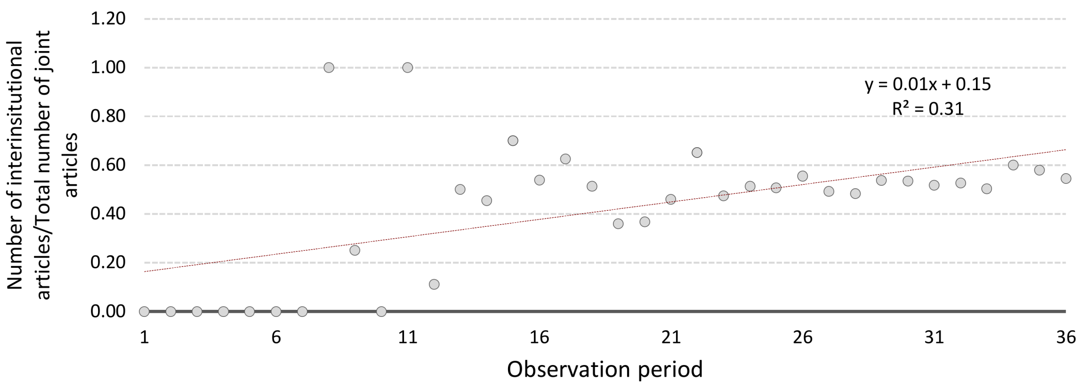


**Figure 3.** The share of the interinstitutional articles in the total number of joint articles ($N$ = 2949). Observation period 1983–2018.

In the studied period, international articles defined as the articles co-signed by authors affiliated with at least two different countries were a minority (22.45%). The average percentage of international articles in the total number of joint articles was 16%, while the median number was 21%. The countries engaged in the co-authorships totaled 124. The vast majority of international articles were written by authors affiliated with two different countries (80.21%). Fewer collaborative efforts were taken between authors affiliated with three different countries (13.60%). Articles written by authors affiliated with four and more different countries constituted only 6.19% in the total number of international articles. The maximum size of co-authorship in terms of internationality was 10 different countries (two articles). Across the studied years, the average team size in terms of internationality was 1.30 countries. In the beginning, international cooperation in terms of research articles practically did not exist; only two internationally co-authored articles have been published over the first thirteen years (1991 and 1993, respectively) since the publication of the first joint article in 1983. The regular publishing efforts in terms of international articles started in 1996. The share of international articles has tripled, from 0.09 in 1996 (only one international article) to 0.24 in 2018 (107 international articles). The number of international articles increased in the last four years, since about half of the total number of such articles have been published from 2015 to 2018 (325 of the total 662 articles). The trend in the share of international articles in the total number of joint articles is increasing (Figure 4); the increase is statistically significant ($t$ = 5.3116, $p$ = 2.0322 for the 34 degrees of freedom, where $p$ is a statistic from LINEST), while the fit is unsatisfactory ($R^2$). Likewise, in the previous case displayed in Figure 3, the rising trend in the relative numbers of international articles is an incidental effect. The fluctuations in the relative numbers of international articles were relatively minor. The distribution was flat in the last eight-year period (2011–2018); the average percentage of the international articles in that period was 23%.

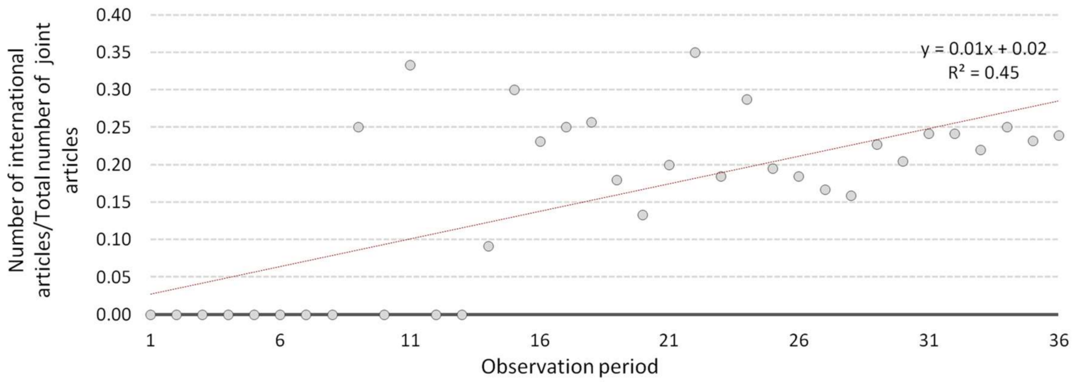


**Figure 4.** The share of international articles in the total number of joint articles ($N$ = 2949). Observation period 1983–2018.

Cross-sector articles were defined as articles co-signed by authors affiliated with at least two institutions related to two different sectors, namely, science and research, government, private sector, NPOs and others. In the studied period, cross-sector articles constituted 20.31% of the total number of joint articles, while the average percentage was 14% and the median number 19%. The first cross-sector article was published in 1991, while the regular output of the cross-sector articles started in 1997. Figure 5 displays an increasing trend. Even though the trend is statistically significant ($t$ = 4.8179, $p$ = 2.0322 for the 34 degrees of freedom where $p$ is a statistic from LINEST), the increase in incidental in the whole time period. The low value of the coefficient of determination ($R^2$) implies an unsatisfactory fit and weak explanatory of the model.

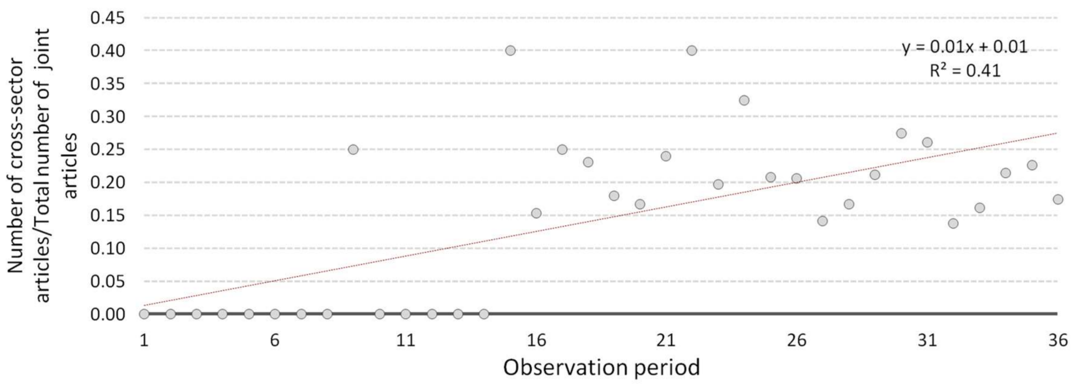


**Figure 5.** The share of cross-sector articles in the total number of joint articles ($N$ = 2949). Observation period 1983–2018.

In the case of interindividual collaboration related to the number of authors of joint articles, we observed a statistically significant increase. More specifically, in the first years, the percentage of joint articles in the total number of articles in sustainable mining was 50% in 1983, 0% from 1984 to 1989 and 22% in 1990, while in 2018 the percentage of joint articles was 87%. This is not surprising as the phenomenon of the growing number of co-authorships has also been found across the fields [37], as well as in specific areas [38–40]. Since we could not reject the null hypotheses in testing the trends in the case of relative numbers of different types of joint articles (interinstitutional, international and cross-sector ones), it is plausible to state that the share of these articles in the total number of joint articles is stable over the studied time period. A lack of increase in the share of interinstitutional, international and cross-sector articles in the total number of joint articles was against our expectations. From the bibliometric point of view, an increase in the number of international articles in sustainable mining could have a positive impact on this research area, since it has been proven that internationally co-authored articles attract more citations [28,41]. However, it is worth mentioning that across the studied years, the number of international articles accounted for 22.45% in the total number of joint articles in sustainable mining and 15.69% in the total number of all articles in sustainable mining. Even though this is a minority, this result is very close to the global percentage of internationally co-authored articles [22,37].

In the studied period, teamwork in terms of publication activity in sustainable mining has increased, while single-authored articles decreased. With reference to the study by de Solla Price [19], Beaver [13] claimed that after WWII the organization of research changed from ‘little science’ (traditional collaboration formed by a small number of co-authors) to ‘big science’ (teamwork constituted by giant collaborations of numerous labs and institutions). Taking this into consideration, it can be assumed that sustainable mining is characterized by traditional collaboration in terms of the size of the co-authorships (authors, institutions, and countries). In the studied period, the average number of team size was 3.88 authors, which is very similar to the result obtained by Wuchty et al. [39], and the vast majority of joint articles was co-signed by up to five authors (83.94%). As Wagner et al. [42] have noticed, some examples of small collaborations may result from the need for shared resources by distinct scientists and their institutions. A summary of the data is presented in Table 1.

**Table 1.** Team size in terms of co-authorships of articles published from 1983 to 2018.

| Analyzed Articles | Number of Articles |
|---|---|
| Interindividual collaboration (collection of $N$ = 3070 articles) | |
| Joint articles: | 3070 |
| 2 authors | 921 |
| 3 authors | 752 |
| 4–5 authors | 904 |
| 6–10 authors | 444 |
| 11–20 authors | 44 |
| ≥ 21 authors | 5 |
| Inter -institutional, -national and cross-sector collaboration (collection of $N$ = 2949 articles) | |
| Single institution articles | 1375 |
| Interinstitutional articles: | 1574 |
| 1 institution | 1376 |
| 2 institutions | 1023 |
| 3 institutions | 365 |
| 4–5 institutions | 141 |
| 6–10 institutions | 40 |
| ≥ 11 institutions | 4 |
| Single country articles | 2287 |
| International articles: | 662 |
| 1 country | 2287 |
| 2 countries | 531 |
| 3 countries | 90 |
| 4–5 countries | 33 |
| ≥ 6 countries | 8 |
| One sector articles | 2350 |
| Cross-sector articles | 599 |

### 3.2. Network Analysis

In order not to limit the considerations to quantitative statistical analyses, we also examined the phenomena of cooperation at the level of individual units (institutions or countries). This was done by means of calculating the strength of cooperation between each pair of objects of the analyzed set. For such defined relationships between objects, a layout algorithm was applied, working in such a way that the objects with stronger links were placed closer together. We call this collaboration 'maps' because the spatial arrangement of objects works here as in the case of cartographic maps—the closer two objects are next to each other, the closer they are in the sense of willingness to cooperate. Of course, with the maps created in this way, the orientation towards cardinal directions does not matter and is arbitrary.

In Figure 6, the collaboration network (graph, 'map') among institutions is shown. The average degree of a node is 3.2, which means that an institution cooperated on average with just over three others. Therefore, this network is a fairly sparse one. It is worth noting that the original graph contained many nodes representing individual institutions, which made it difficult to read, so some of the least productive institutions were filtered out in Figure 6. Despite this, it is still quite difficult to analyze in a printed form, and the following conclusions have been drawn based on interactive analyses performed with the Gephi tool, i.e., zooming in, scrolling and previewing the values of individual most distinctive nodes or edges. Here is how to read this 'map': The bigger a node, the more active it is in the field of collaboration. The thicker the edge linking two nodes, the more intensive collaboration between these two nodes it indicates. This includes two opposite situations when, in one case, a given institution works out its collaboration factor by intense collaboration with a limited number of others, and in the other case, the collaboration is limited, but there are many collaborators. In addition, it should be emphasized that the layout of institutions is not random. The layout algorithm groups together nodes that are related to each other—the thicker is an edge between two nodes, the stronger is the binding, so the shorter distance is between them. Strongly cooperating institutions are located next to each other, while those that do not cooperate are distant from each other. In addition, the colors of the nodes represent the country of a given institution—this allows easy assessment whether the cooperating neighbor is a national or a foreign one. In the studied period, the five most active institutions in terms of co-authorships were (in descending order):

- The Chinese Academy of Sciences (China),
- The University of Queensland (Australia),
- The University of California (The United States),
- Commonwealth Scientific and Industrial Research Organization—CSIRO (Australia),
- The United States Department of the Interior, Washington DC (The United States).
- The two most cooperating institution pairs were:
- CSIRO (Australia)—The University of Queensland (Australia),
- AGH University of Science and Technology (Poland)—the Polish Academy of Sciences (Poland).

Looking at the collaboration 'map,' we see in the 'south' a large area covered by magenta (China) nodes, but only two of them have an outstanding size (the Chinese Academy of Sciences and China University of Geosciences). More 'southwards' but confluent with magenta nodes we see the pink ones (Japan) with the biggest one—The University of Tokyo. In the center of the map, thus the most willing to cooperate, the green nodes (United States) can be observed nearby the aquamarine ones (Australia). Further to the 'north,' European institutions can be found, but the more we move outside to the 'north,' the more isolated entities we see. What is quite interesting is that the very outside (where there are usually small, and therefore, uncooperative institutions) there is one large node—the Russian Academy of Sciences. This may indicate the relative isolation of this institution from other leading research institutions, and it owes its significant size to the cooperation with many other very small entities. In fact, looking into detailed data, we may confirm that this institution cooperated with almost 40 others, but most of them are of minor importance, except for Luleå University of

Technology (Sweden), which in turn cooperated with almost 30 others. In general, we can also notice a tendency to group nodes with the same colors—this indicates a greater willingness to cooperate between institutions located in the same countries.

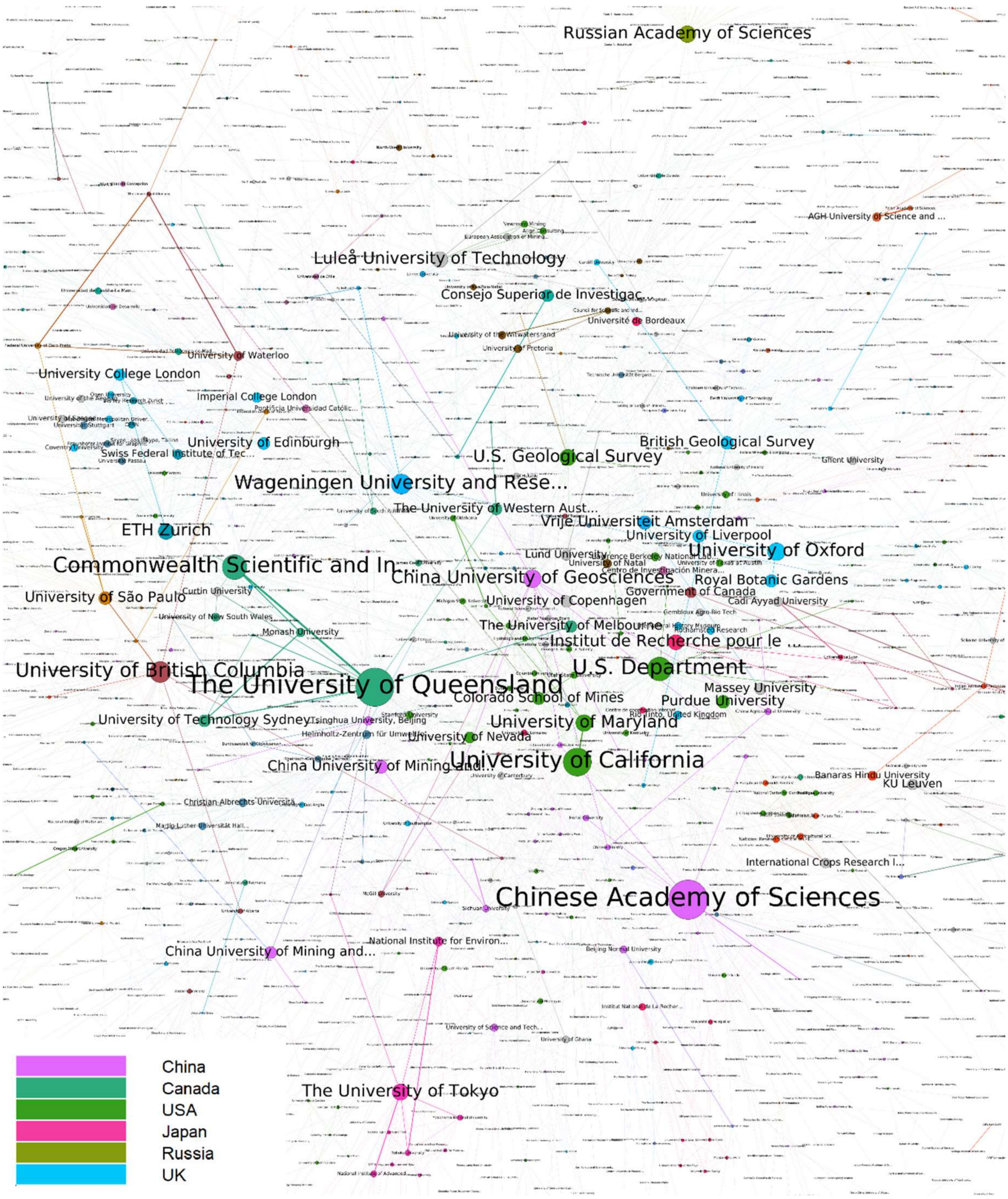


**Figure 6.** The collaboration network among institutions.

The number of countries engaged in joint articles increased from up to 10 until 1998 to 79 countries in 2018. The vast majority of countries (117 countries, 94.35% of the total of countries engaged in co-authorships) were engaged in collaboration. Regarding the network nature of collaborating countries, the average node degree is 9.3; however, analyzing Figure 7, we have to conclude that the distribution of node degrees is far from being uniform. There are many countries poorly cooperating (above 5% of countries, not shown in the figure, have not co-authored with other ones at all). On the other hand, there are numerous ones with great inclination to cooperate.

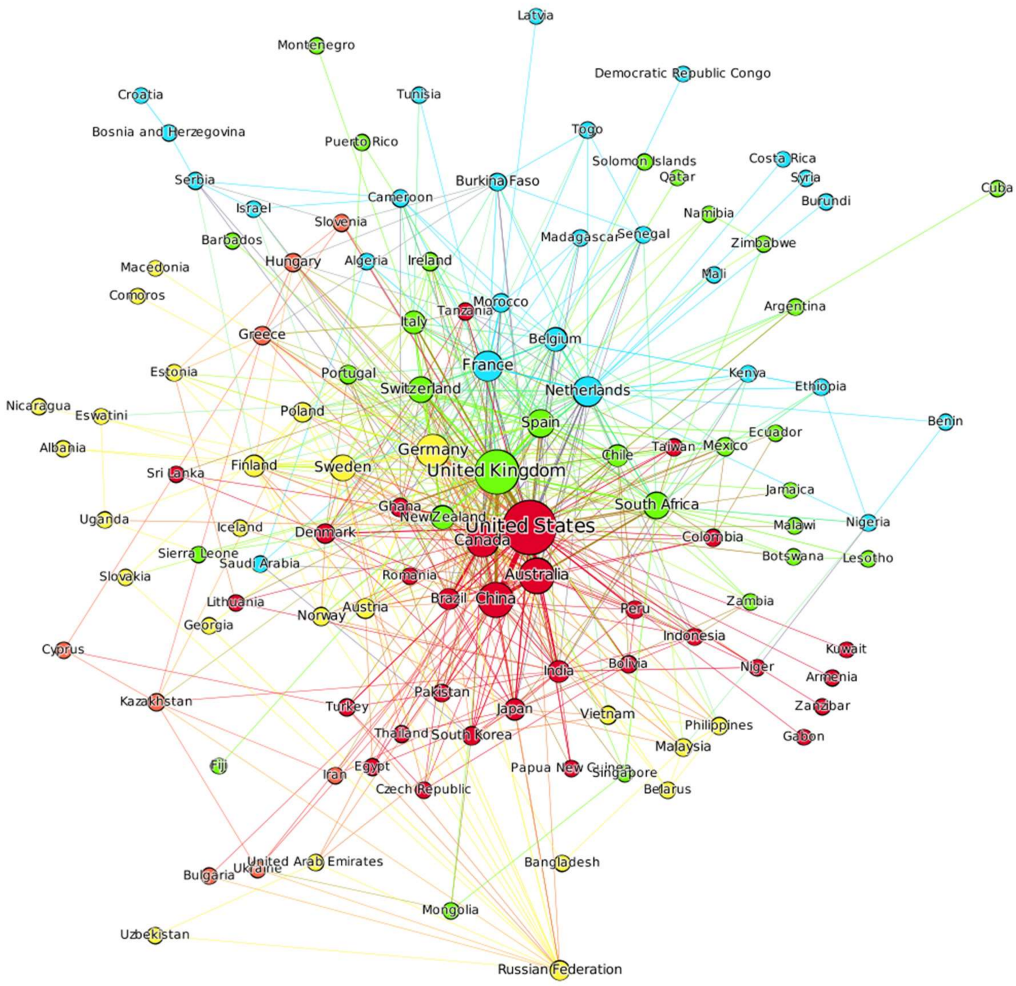


**Figure 7.** The collaboration network among countries.

The most cooperating countries include (in descending order): The United States, the United Kingdom, Australia, China, Germany, Canada, France, the Netherlands, Spain, South Africa, Sweden, and Switzerland. The most active pairs in terms of cooperation are (in descending order):

- The United States—China,
- The United States—The United Kingdom,
- Australia—China,
- The United Kingdom—China,
- The United States—Australia,
- The United States—Canada.

For the purpose of the study, we employed a community detection algorithm to suggest cooperating clusters, and then we colored the nodes according to them. In Figure 7, a clear red cluster representing the majority of the most cooperating countries can be observed. What is quite noteworthy is that the hub is cross-continental and includes both Americas, Australia, Asia and to some minor extent Europe and Africa. The other three colors (blue, red, yellow) representing subsequent clusters are slightly more geographically polarized, and only individual cases disturb them. Interestingly, the leading European countries such as the United Kingdom, France and the Netherlands, as well as Germany and Sweden, have found their ways into various clusters. Of course, the community detection algorithm is parameterized, so it would also be possible to reduce the number of detected hubs; however, the effects obtained in the figure seem justified and inspiring. Significantly, once again, Russia is positioned on the boundary of the map, noting only a few cases of cooperation with countries such as Japan, Bulgaria, Ukraine, Kazakhstan, Turkey, and Egypt. Although the above considerations are quite descriptive, we can conclude that many countries are collaborating on sustainable mining, which testifies they found their common interest and understanding of this topic. The only significant exception here, at least observed from data collected, is Russia. This split may exist, but may not need to, it could be evidence of a slightly different approach to sustainable mining in Russia.

The biggest sector in terms of the number of institutions engaged in the co-authorships was science and research, namely, universities, research institutes, academies of sciences (68.47%), the second biggest was the private sector (19.43%), while the government, non-profit and others were in minority (7.70%, 3.45%, and 0.96%, respectively). Figure 8 displays the relations between individual sectors regarding joint articles. It visualizes in a circular layout the collaboration shared among individual institution types, namely, science and research (in blue), government (in green), private (in red), non-profit (in yellow), and other (in azure). Of course, not only the collaboration between different institution types can be exhibited by this chart, but also cooperation within one type. Outer rings of this chart can be used to read both percentages and absolute values of the cooperation share. It is a visualization technique taken from the field of bioinformatics used to illustrate directed relations, however, because cooperation is a symmetrical relationship, the values resulting from the three outermost rings should be interpreted with caution. The most active sector in terms of joint articles was science and research. In the studied period, the authors affiliated with academic and research institutions collaborated with authors representing all sectors considered in this article. Mostly, they collaborated with other authors affiliated with science and research institutions (approximately 65.2% of joint articles). Fewer collaborative efforts by researchers were taken with the authors representing the private sector (approximately 17.5%) and the government (approximately 12.4%).

Our network analysis showed that the most active institution in terms of co-authorships was the Chinese Academy of Sciences (CAS). We would like to highlight here the method of cleaning the data in terms of the names of institutions which we have used. All distinct institutes of CAS were treated as one institution. Therefore, this large research organization comprising over 100 institutes has the advantage over the other units all over the world. The case of CAS is interesting because the study in materials science [43] showed that CAS not only has a lot of domestic linkages, but that it also plays an intermediary role between Chinese institutions and foreign partners. The collaboration network among the countries engaged in sustainable mining in terms of publication activity demonstrated that the most cooperating countries were representing different continents, so the research collaboration was undertaken regardless of geographical distance. Surprisingly, this result is different from that one which was obtained in the study on research collaboration in sustainability science in general [44]. A recent study [1] displayed some gaps in the sustainable mining publications related to the 17 Sustainable Development Goals, e.g., poverty eradication, quality education, gender equality, innovation and infrastructure, reduced inequalities, climate action. Socio-economics could contribute to the field of sustainable mining within research on mining investments which support the poverty reduction in low-income countries. Another absent topic is gender in engineering (here, in mining) workplace culture. Therefore, the global character of the research collaboration for sustainable development of the mining sector could contribute to filling this gap. The analysis of the patterns of cross-sector co-authorships showed that the vast majority of joint articles is co-signed by authors affiliated with science and research institutions. Moreover, almost 65.2% of collaborative efforts were limited to this type of institution. This is not surprising since such collaboration closed mostly within one sector, namely, science and research, can be explained by sharing the same interest, namely, an increase in publication output which is the accountable result of research activity and also a key point in the evaluation of grants submission forms. Even though the collaboration between different sectors is difficult and requires the understanding of each party (cf. [15]), such collaboration is possible and should be fostered by government or international research programs.

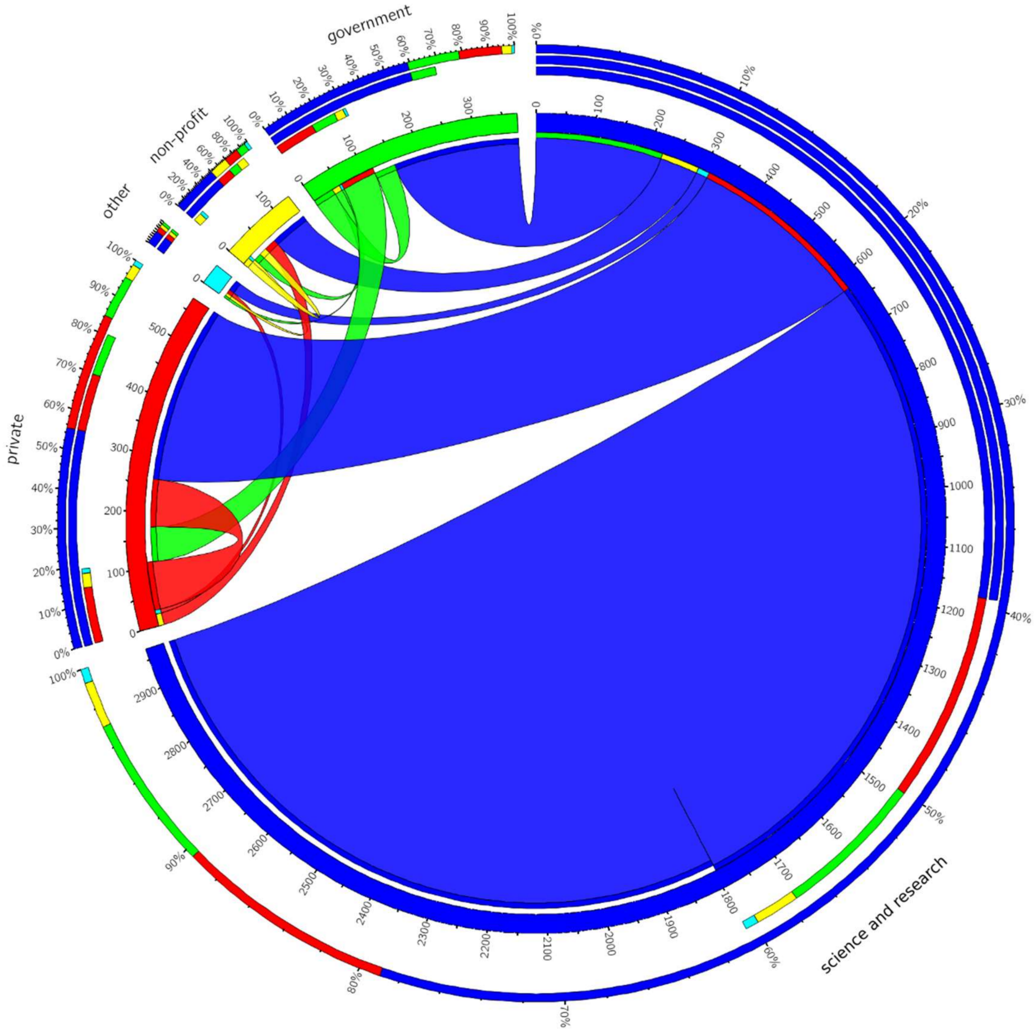


**Figure 8.** The chart of collaboration among institution types.

## 4. Discussion and Conclusions

Research on collaboration based on a bibliometric approach is the emerging field. A growing number of different research fields apply bibliometric methods to analyze patterns of collaboration. Data cleaning in bibliometrics is the most labor-intensive and time-consuming part of the research process. In this study, at the stage of data cleaning we had to deal with numerous variants of institution names, names of the same institution which were frequently written in different languages (native and English), and incomplete information about affiliation. Responsibility for reliable data provided in authors' institutional addresses lies on both sides, the authors of the articles and the editors of journals. Authors and their institutions should care about proper identification in terms of affiliation, due to the mechanisms of evaluation systems that use authors' addresses to build world rankings in science or distribute funds at the national level. Finally, the authors themselves have an interest in reliable information about their affiliation, because unambiguous identification supports visibility in the research community. Journal editors should also care for the high quality of published data, which is particularly important because the publishing market has been struggling with the phenomenon of predatory publishing for years.

In general, this study showed that although sustainable mining has the potential reflected in numerous institutions and countries engaged in research, their involvement in co-authorships is in the minority, and the network is sparse. It could be influenced by external factors such as relatively small funds allocated for research in this area, or internal factors, i.e., the small capacity of the community to cooperate. Therefore, if sustainable mining does not want to be 'sustainable' only in the name, cooperative efforts should be intensified. The Brundtland report [2], which was identified as the most cited publication in the sustainable development literature [45], constituted a milestone in forming this approach. Our bibliometric analysis demonstrated that, not long after the release of this report, the community associated with the research in sustainable mining responded to the new challenges posed to the mining sciences and the mining industry by publishing research articles in this subject, including joint articles. Based on the Scopus dataset, we pointed out that regular co-authorship efforts, meaning articles published year by year without any breaks, began in 1990. This study also showed that the higher the level of research collaboration in terms of co-authorships in sustainable mining expands (from interindividual, through interinstitutional, to international), the later regular collaborative efforts appear (1990, 1993, and 1996, respectively). A trend analysis applied to test the hypotheses concerning relative numbers of joint articles showed that interindividual collaboration characterized by an increase over the studied period. The collaborative efforts in sustainable mining articles may result from interdisciplinarity. The idea of sustainability itself implies an interdisciplinary character of this field. However, one has to keep in mind that the structure of sustainability science in terms of interdisciplinarity is unequal [46]. On the other hand, the increasing specialization of researchers may cause the necessity of work dividing and may result in a growing number of co-authorships [47]. In the case of sustainable mining, joint articles may result from both interdisciplinarity and growing specialization. In this context, it is worth mentioning that the descriptive statistics performed in the team size analysis showed that the average number of authors, institutions and countries was rather small, namely, 3.88 authors, 1.85 institutions and 1.30 countries per article. Nevertheless, co-authorship as a formal manifestation of research collaboration fosters sustainable development [48], and the high share of joint articles in the total number of articles regarding sustainable mining may be considered as a part of this idea. The share of interinstitutional articles in the total number of joint articles was 53.37%, while the international and cross-sector articles were a minority (22.45% and 20.31%, respectively). Moreover, the network analysis showed that collaborative efforts were taken mostly between authors affiliated with the science and research sector (68.47%). Even though the percentage of international articles in sustainable mining did not differ from the results obtained in other studies, the funding agencies should stimulate more international and cross-sector research collaboration in this area to further develop the idea of sustainable mining. The network analysis, in terms of research collaboration between the countries engaged in sustainable mining, demonstrated that this collaboration has an intercontinental character. However, studying the collaboration 'maps' developed in this article suggests geopolitical barriers which are difficult for countries to overcome while working on such a globally desirable topic. Finally, we all must understand that working together could effectively solve long-term issues and support the sustainable development of the mining sector.

**Supplementary Materials:** The following detailed data are available online through Zenodo at https://doi.org/10.5281/zenodo.3783598, Table S1: Distribution of articles in sustainable mining from 1983 to 2018. Raw data obtained from Scopus on 29th of April 2019, Table S2: Distribution of joint articles and the types of joint articles from 1983 to 2018. Data after cleaning obtained from Scopus on 29th of April 2019, Table S3: Team size in terms of the number of authors of articles in sustainable mining from 1983 to 2018. Raw data obtained from Scopus on 29th of April 2019; Table S4: Team size in terms of the number of authors' institutions in articles in sustainable mining from 1983 to 2018. Data after cleaning obtained from Scopus on 29th of April 2019, Table S5: Team size in terms of the number of authors' countries in articles in sustainable mining from 1983 to 2018. Data after cleaning obtained from Scopus on 29th of April 2019.

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